PERFORMANCE EVALUATION ESTIMATORS FOR WATER QUALITY MONITORED STREAMS

FEBRUARY 1992

Ontario
Environment
Environnement

ISBN: 0-7729-7650-3

PERFORMANCE EVALUATION ESTIMATORS FOR WATER QUALITY MONITORED STREAMS

Report Prepared by:

Water Resources Branch
Ontario Ministry of the Environment

FEBRUARY 1992

PRINTED ON
RECYCLED PAPER
IMPRIMÉ SUR
DU PAPIER RECYCLÉ

Cette publication technique
n'est disponible qu'en anglais.

PIBS 1865
log 90-2309-044

PERFORMANCE EVALUATION ESTIMATORS FOR WATER QUALITY
MONITORED STREAMS

Lloyd A. Logan
Water Resources Branch
Ontario Ministry of the Environment
Toronto, Ontario M4V 1P5

ABSTRACT

Provincial water quality objectives were established by the Ministry of the Environment to protect ambient water quality conditions in Ontario rivers. The rivers and streams play useful roles in diluting and assimilating wastewaters. In addition, there are several guidelines and regulations which allow the introduction of pollution control measures. Uncertainties are imbedded in the system due to the variabilities and randomness present in the streamflows and in the point-source and diffuse-source pollutions. This paper presents an attempt to evaluate performances using probability concepts of reliability, resiliency and vulnerability. The performances of several rivers are judged by the capability of the rivers to maintain water quality conditions to requirement of provincial water quality objectives, their ability to recover from failure and the significance of the consequence of failure. It is concluded that this approach is effective in establishing estimators to evaluate performances of rivers relative to specific water quality objectives and providing a tool to examine the system responses to alternate policy objectives.

INTRODUCTION

The Ontario Ministry of the Environment has the responsibility to maintain the quality of water in a state which is satisfactory for aquatic life and recreation. The water quality in the rivers and streams throughout the province is closely surveyed under a Provincial Water Quality Monitoring Network Program. The purpose is to protect against degradation in quality. The water quality in Ontario streams is expected to satisfy the Provincial Water Quality Objectives (PWQO) [1].

The Ministry regulates control measures for waste discharges. The streamflow that augments dilution and assimilation of wastewater varies in time and space and is stochastic in nature. In addition, the diffuse-source pollution varies considerably and is difficult to control. These

variabilities, being random, add uncertainties to the system. Therefore, a technique is required to evaluate the capability of the stream in maintaining water quality at conditions better than specified water quality objectives. A suitable technique is the performance evaluation criteria; which is based on probability concepts of reliability, resiliency and vulnerability. Performance evaluation concepts were used to evaluate water resources systems [2], reservoir system operations [3], [4] and drought flows in Ontario [5]. The objective of this paper is to develop performance evaluation estimators for rivers and streams, using probability criteria, from which the ambient water quality conditions could be compared with established objectives.

PERFORMANCE ESTIMATORS

The performance evaluation estimators are developed from the probability concepts of reliability, resiliency and vulnerability [2].

Let x_t be the water quality concentration assumed to be Gaussian distributed. If x_t does not violate a specified threshold-value objective, then, the water quality system is in a satisfactory state, S, with reliability, α, defined as:

[1] $\alpha = P\ (x_t \ \varepsilon\ S),\ t = 1,2,\ \ldots.,\ n;$

from which, risk or probability of failure is defined as: $1-\alpha$.

When the system is not in a satisfactory state it is in a failure state, F. The degree to which the system recovers from failure is the resiliency, γ . This is a measure of the probability that the system will recover from failure immediately following the occurrence of a failure:

[2] $\gamma = P\ (x_{t+1}\ \varepsilon\ S \mid x_t\ \varepsilon\ F).$

The system operates in transition from a failure to a satisfactory state and vice versa. Consider the normalized process which is defined as unity in state S, and zero in state F:

$Z_t = 1$, if $x_t\ \varepsilon\ S$; and $Z_t = 0$, if $x_t\ \varepsilon\ F$.

In the limit, as $n \to \infty$ the fraction of time the system is in State, S, approaches the probability α; that is:

[3] $$\lim_{n \to \infty} (1/n) \sum_{t=1}^{n} Z_t = \alpha = P\ (x_t\ \varepsilon\ S).$$

Similarly, consider the normalized process in transition from a satisfactory to an unsatisfactory state:

$W_t = 1$, $x_t\ \varepsilon\ S$ and $x_{t+1}\ \varepsilon\ F$; and
$W_t = 0$, otherwise.

Therefore, in the limit, as $n \to \infty$ the fraction of time the system remains in a satisfactory state, S, in some period, t, subsequent to transfer to the failure state, F, in period, t + 1, approaches the probability, ρ:

$$[4] \quad \lim_{n \to \infty} (1/n) \sum_{t=1}^{n} W_t = \rho = P\,(x_t \in S \text{ and } x_{t+1} \in F).$$

The expected time, $E\,[T_f]$, the system is in temporary resident in the failure state, can be estimated by:

$$[5] \quad E\,[T_f] = (\text{total number of events spent in F})/(\text{number of times F occurred})$$
$$= P\,(x_t \in F) \,/\, P\,(x_t \in S \text{ and } x_{t+1} \in F)$$
$$= (1 - \alpha)/\rho.$$

By definition resiliency, γ, is the reciprocal of $E\,[T_f]$:

$$[6] \quad \gamma = 1/E\,[T_f] = \rho \,/\, (1 - \alpha).$$

Further, in the limit, as $n \to \infty$ the probability of entering a failure state from a satisfactory state is equal to the probability of entering a satisfactory state from a failure state; which implies that resiliency is equal to the probability of recovery from the failure state in a single time step:

$$[7] \quad \gamma = P\,(x_t \in F \text{ and } x_{t+1} \in S) \,/\, P\,(x_t \in F)$$

$$= P\,(x_{t+1} \in S \mid x_t \in F).$$

The consequence of a failure situation can be evaluated in terms of cost to recover from failure, risk to human health or impact to the aquatic species. Decision-makers endeavour to minimize risk by increasing the efficiency of sewage and industrial plants and by implementing remedial actions. Vulnerability is a measure, involving intensity and duration, which can be used to assess the significance of the consequence of failure.

Generally, a water quality condition is violated if a specified threshold-value objective is exceeded. Let x and x_j be the observed concentration and the specified threshold objective, respectively. The probability of violation, π, under a Gaussian assumption is:

$$[8] \quad \pi = P\,(x > x_j) = \int_{x_j}^{\infty} f\,(x)\,dx$$

for an upper limit threshold-value objective or

$$[9] \quad \pi = P\,(x < x_j) = \int_{-\infty}^{x_j} f\,(x)\,dx$$

for a lower limit threshold-value objective. Vulnerability for discrete observations, is defined as:

$$[10] \quad \nu = \left(\sum_{k=1} \pi_k \; d_k \right) \Delta\, T/T,$$

where, π_k is the probability of violation of a discrete failure; and d_k is the degree of failure estimated by the most severe failure outcome, x_k, that occurred:

$$[11]\quad d_k = \begin{cases} (x_k - x_j), & \text{upper limit threshold objective} \\ (x_j - x_k), & \text{lower limit threshold objective} \end{cases}$$

in which ΔT is the severe failure period and T is the total failure duration used to standardized d_k. π_k defines the frequency and takes into account the duration dimension of failure and d_k is the magnitude which accounts for the intensity dimension of failure.

APPLICATION

Total phosphorus, nitrates, copper and total suspended solids are the parameters used in deriving the performance evaluation estimators for the rivers. The objectives 0.01 to 0.03 mg/l for total phosphorus were established to prevent excessive growth of aquatic plants which impair water quality. Nitrates also promote excessive growth of algae. Due to the toxic effect of nitrates to infants an objective of 10 mg/l for drinking water was established. Free aqueous copper ions are extremely toxic to fish, therefore, an objective 0.005 mg/l was specified for copper ions. Total suspended solids, on the other hand, has a guideline of 250 mg/l.

The performance evaluation estimators for the Great Lakes' Rivers Grand, Sydenham, Saugeen, Kaministiquia and Humber (Figure 1) are shown in Tables 1 to 4. The estimators were derived using monthly records for the period 1965-85 in which arbitrarily selected policy objectives were used as threshold-values. Pollution sources are industrial and municipal plants, mixtures of industrial and municipal plants, agricultural areas and combination of agricultural and urban runoff areas. Examples of performance evaluation curves for the Grand and Saugeen Rivers are shown in Figures 2 and 3 for total phosphorus and nitrates.

The tributary performances for total phosphorus at PWQO levels of 0.01 mg/l and 0.02 mg/l at the Grand River have not been satisfactory; only PWQO of 0.03 mg/l was met at a 0.6% reliability, with resiliency 0.013 and vulnerability 1.44 mg/l/month. This indicated that with such poor performance the system would remain in failure over a long period of time allowing growth of algae and subsequently, poor aesthetic conditions before any possible recovery. Similarly, the vulnerability indicated that significant reduction in levels of total phosphorus is required in order to achieve meaningful improvement in performance.

The Sydenham, Kaministiquia and Humber Rivers showed similar results for total phosphorus at PWQO of 0.03 mg/l, but of lesser degree, indicating reliability of 9%, 16% and 2.4%, respectively. The performances at the PWQO 0.01 mg/l and 0.02 mg/l levels were unsatisfactory, suggesting extended failure sequences following the occurrence of a failure. Similarly, the larger vulnerabilities indicate a need for remedial actions.

Performance evaluation for copper when examined at the PWQO level of 0.005 mg/l showed reliabilities of 26%, 29%, 47%, 61% and 22% at Grand, Sydenham, Saugeen, Kaministiquia and Humber Rivers, respectively. This indicated low measures of reliability. The extent of failure can be examined from the inverse of the resiliencies. For example, at the Grand, Sydenham, Saugeen, Kaministiquia and Humber Rivers the inversed resiliances are 5.4 months, 6.6 months, 2.7 months, 1.8 month and 6.7 months, respectively. These values are the recurrences, the times to

recover following the occurrence of a failure. The vulnerability values in copper are significant especially at Sydenham.

The performance evaluations for total suspended solids and nitrates are satisfactory for most times for threshold-value objective levels of 100 mg/l and 5 mg/l, respectively. The Grand, Sydenham, Saugeen, Kaministiquia and Humber Rivers showed reliabilities for suspended solids of 88%, 89%, 100%, 99% and 88%, respectively, with resiliencies indicating immediate recovery once failure occurred. Similarly, reliability for nitrates at threshold level of 5 mg/l is at 100% at Grand, Saugeen and Kaministiquia and Humber Rivers. Sydenham, on the other hand, showed reliability of 88%, and a resiliency recovery time of 1.3 month once failure occurred. It should be noted, however, that nitrates level of 0.5 mg/l, as expected, is satisfactory only at the Kaministiquia River.

DISCUSSION

High levels of total phosphorus in the Grand and Humber Rivers demonstrated unsatisfactory performance suggesting inability to prevent incidences of algae and plant growths and allowing period of nuisance growth prior to a recovery. In the industrial area at the Kaministiquia River, the performance for total phosphorus is also low; at PWQO of 0.03 mg/l, the 16% reliability and 7.2 months for recovery necessary after a failure showed that effective remedial actions would be required. The Saugeen River, on the other hand, showed better performance, for example, with total phosphorus at PWQO level of 0.03 mg/l a more effective response is observed indicating a shorter recovery time following a failure. The more agriculturally developed Sydenham basin showed a reliability of 8%, a resiliency of 0.09 (γ^{-1} = 11 months) and a vulnerability of 2.9 mg/l/month at a PWQO level of 0.03 mg/l. Therefore, in order to prevent an increase in the total phosphorus levels in the Saugeen River preventive measures should be practiced. The Grand River also demonstrated high vulnerability indicating less capacity to recover naturally, as compared with the Saugeen River which showed greater capacity to recover naturally without need for major remedial actions.

The performances for nitrates and total suspended solids are satisfactory for all rivers at the PWQO level and the guideline, respectively, implying less cause for concern regarding impacts on water quality. However, caution should be placed on Grand, Sydenham and Humber Rivers which showed marked reduction in performances at smaller threshold-value objectives.

The application of the stream performance evaluation estimators as a system analysis tool is demonstrated with alternate policy objectives examined under consecutive failure periods. For example, copper at the PWQO of 0.005 mg/l demonstrated a range of resiliency over consecutive failure periods. Recommendations for improvement would depend on the lethality of fish over the time period the system takes to recovery. If long duration in failure is a factor, then some remedial actions would be required. The Saugeen and Kaministiquia rivers showed better resiliency responses at the PWQO of 0.005 mg/l; indicating shorter time to recover following a failure. In these situations, concerns remained, nonetheless, on the potential impact to fish species. Under consecutive periods of failure events and with given threshold-value objective the resiliency tends to increase with a reduction in recovery time; therefore, the chance for survival of tolerant species under these conditions would be enhanced. Typical relationships of resiliencies and change in policy objectives for copper ions are shown in Figure 4. In this case, with the use of a

threshold objective of 0.003 mg/l, instead of the PWQO of 0.005 mg/l, under consecutive failure periods, gives a less responsive resiliency and a longer failure sequence, hence a greater recovery time. Therefore, the decision-maker has a choice to select a policy, based on the degree of water quality protection required.

CONCLUSION

The performance evaluation concept is developed to examine and assess streamflow behaviours for maintaining ambient water quality conditions for total phosphorus, total suspended solids, nitrates and copper at levels compared with objectives. An assessment of five Great Lakes' Rivers indicated poor performances for total phosphorus at all PWQO levels; suggesting that there has been little or no protection to prevent deterioration in aesthetic conditions and nuisance growth of algae and plants. Appreciable stream performance for total phosphorus at PWQO of 0.03 mg/l was observed at the Saugeen River, reflecting the response of a less developed watershed. Satisfactory performance was observed for nitrates at a threshold objective level of 5 mg/l, suggesting limited contribution in promoting and sustaining algae and plant growth. The low performances at nitrates levels of 0.5 mg/l remain a concern. Performances for suspended solids were satisfactory with regards to the guideline.

Serious remedial actions appeared to be required in order to achieve meaningful improvement in stream performance for total phosphorus. No serious impacts could be inferred on nitrates and suspended solids, in that, satisfactory performances have been achieved at low threshold-value objective levels.

Streamflow performance on copper ions suggested that concerted effort on surveillance is required. This has been due to the less than average reliability and the extended period to recover once failure occurred at the PWQO level. The vulnerability, in general, sets the degree of management that is required to achieve meaningful improvement in performances.

REFERENCES

1. Ontario Ministry of the Environment. Water Management, Goals, Policies, Objectives and Implementation Procedures of the Ministry of the Environment. 1978; Revised (1984).

2. Hashimoto, T., J. Stedinger and P. Loucks. Reliability, Resiliency, and Vulnerability Criteria for Water Resources System Performance Evaluation. Water Resources Research, Vol. 18(1), 1982; pp. 14-20.

3. Fiering, M. Estimates of Resilience Indices by Simulation. Water Resources Research, Vol. 18(1), 1982; pp. 41-50.

4. Weerarante, J., L. Logan and T.E. Unny. Performance Evaluation of Alternate Policies on Reservoir System Operation. Canadian Jour. of Civil Eng., 13, 1986; pp. 203-212.

5. Logan, L.A. Drought Flows and Receiving Water Assessment in Ontario. Ontario Ministry of the Environment, 1986; pp. 21.

Table 1. Stream Performance Evaluation Estimators For Total Phosphorus

Reliability (α) = P ($x_t \leq x_j$)

x_j	0.01	0.02	0.03	0.05	0.10	0.20
Grand		0	0.006	0.038	0.242	0.809
Sydenham	0	0.029	0.080	0.264	0.596	0.851
Saugeen	0.033	0.202	0.343	0.709	0.948	0.986
Kaministiquia	0	0.039	0.161	0.161	0.960	1.0
Humber		0	0.024	0.152	0.527	0.855

Resiliency (γ) = P ($x_{t+1} \leq x_j \mid x_t > x_j$)

x_j	0.01	0.02	0.03	0.05	0.10	0.20
Grand		0	0.013	0.027	0.168	0.633
Sydenham	0	0.049	0.090	0.183	0.524	0.807
Saugeen	0.039	0.153	0.257	0.532	0.727	0.800
Kaministiquia	0	0.034	0.139	0.451	0.630	
Humber		0	0.019	0.129	0.423	1.0

Vulnerability (ν)

x_j	0.01	0.02	0.03	0.05	0.10	0.20
Grand			1.440	1.220	0.406	0.135
Sydenham		2.28	2.890	0.919	0.019	0
Saugeen	1.61	0.308	0.260	0.085	0	
Kaministiquia		1.26	0.139	0.017	0	
Humber			8.870	0.186	0.064	0.040

Table 2. Stream Performance Evaluation Estimators For Nitrates

Reliability (α) = P ($x_t \leq x_j$)

x_j	0.5	1	2	3	5
Grand	0.064	0.200	0.457	0.779	1.0
Sydenham		0.394		0.674	0.876
Saugeen	0.359	0.798	0.995	1.0	
Kaministiquia	1.0				
Humber	0.374	0.699	0.976	1.0	

Resiliency (γ) = P ($x_{t+1} \leq x_j \mid x_t > x_j$)

x_j	0.5	1	2	3	5
Grand	0.046	0.107	0.184	0.355	1.0
Sydenham		0.248		0.556	0.797
Saugeen	0.252	0.350	1.0		
Kaministiquia	1.0				
Humber	0.221	0.460	0.75	1.0	

Vulnerability (ν)

x_j	0.5	1	2	3	5
Grand	100.6	15.94	1.46	0.602	0
Sydenham		2.69		0.764	0.629
Saugeen	7.98	0.487	0		
Kaministiquia	0				
Humber	1.06	0.135	0.14	0	

Table 3. Stream Performance Evaluation Estimators For Total Suspended Solids

Reliability (α) = P ($x_t \leq x_j$)

x_j	10	30	50	100
Grand	0.154	0.263	0.487	0.878
Sydenham	0.200	0.732	0.809	0.894
Saugeen	0.518	0.909	0.951	1.0
Kaministiquia	0.613	0.887	0.972	0.993
Humber	0.186	0.528	0.752	0.876

Resiliency (γ) = P ($x_{t+1} \leq x_j \mid x_t > x_j$)

x_j	10	30	50	100
Grand	0.114	0.149	0.288	0.737
Sydenham	0.213	0.730	0.711	0.840
Saugeen	0.304	0.737		
Kaministiquia	0.436	0.813	0.75	1.0
Humber	0.099	0.481	0.725	0.900

Vulnerability (ν)

x_j	10	30	50	100
Grand	184.5	45.4	35.3	0
Sydenham	165.7	8.8	8.1	0
Saugeen	13.8	8.8		
Kaministiquia	15.7	12.2		
Humber	117.6	32.9	32.9	31.4

Table 4. Stream Performance Evaluation Estimators For Copper

Reliability (α) = P ($x_t \leq x_j$)

x_j	0.003	0.005	0.010	0.020
Grand	0.051	0.256	0.727	0.966
Sydenham	0.169	0.292	0.700	0.954
Saugeen	0.197	0.470	0.909	1.0
Kaministiquia	0.152	0.608	0.949	1.0
Humber	0.084	0.221	0.632	0.895

Resiliency (γ) = P ($x_{t+1} \leq x_j \mid x_t > x_j$)

x_j	0.003	0.005	0.010	0.020
Grand	0.054	0.184	0.548	0.750
Sydenham	0.139	0.152	0.564	0.600
Saugeen	0.170	0.370	1.0	
Kaministiquia	0.149	0.548	0.750	1.0
Humber	0.081	0.149	0.486	0.600

Vulnerability (ν)

x_j	0.003	0.005	0.010	0.020
Grand	0.113	0.041	0.0012	0
Sydenham	0.224	0.217	0.0014	0
Saugeen	0.015	0.017	0.0014	0
Kaministiquia	0.004	0.006	0.0007	0
Humber	0.055	0.051	0.0370	0

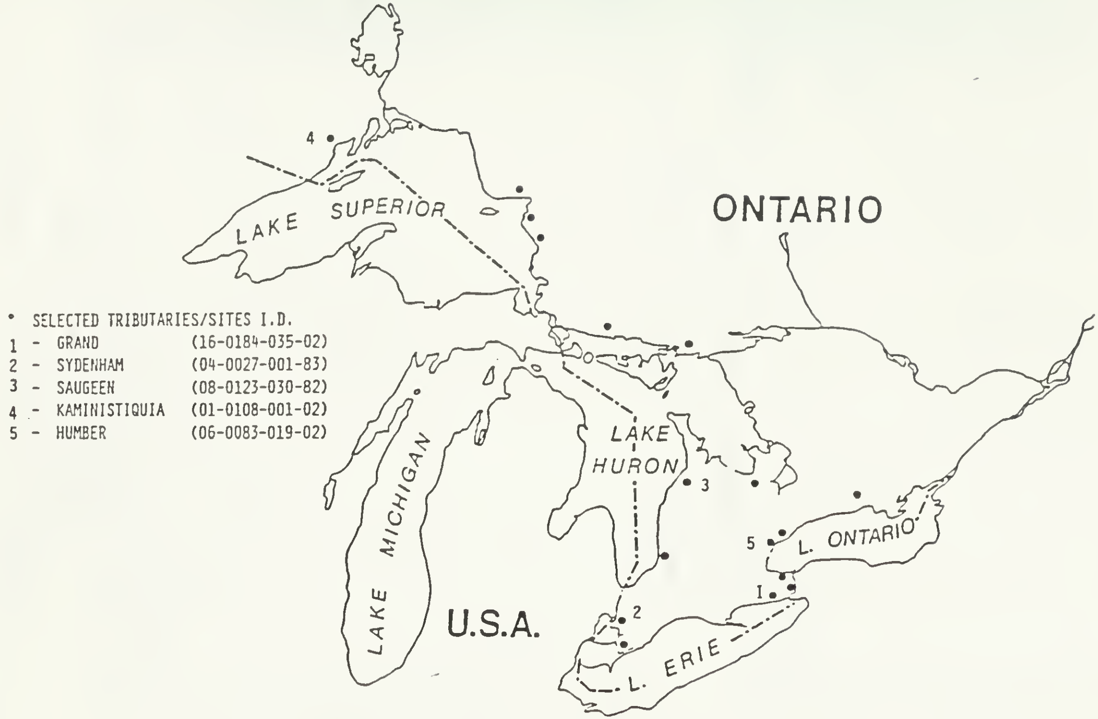

FIG. 1 : LOCATION OF MAJOR TRIBUTARIES MONITORED IN ONTARIO, CANADA

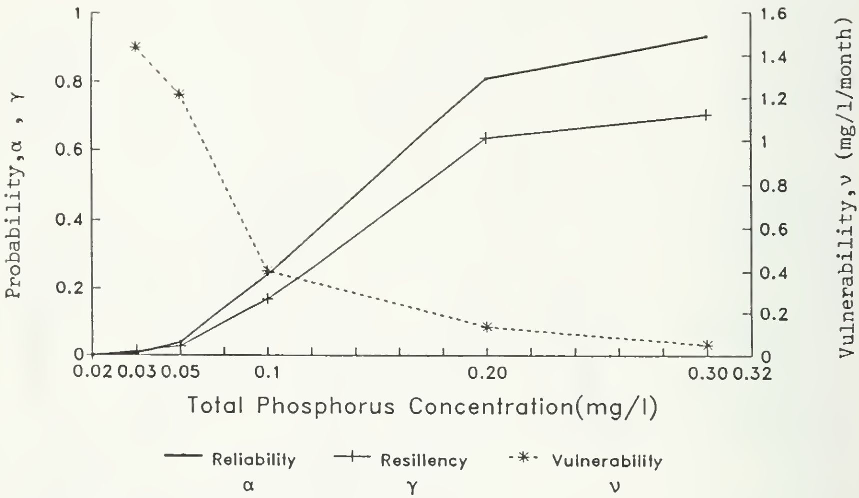

FIGURE 2(a):

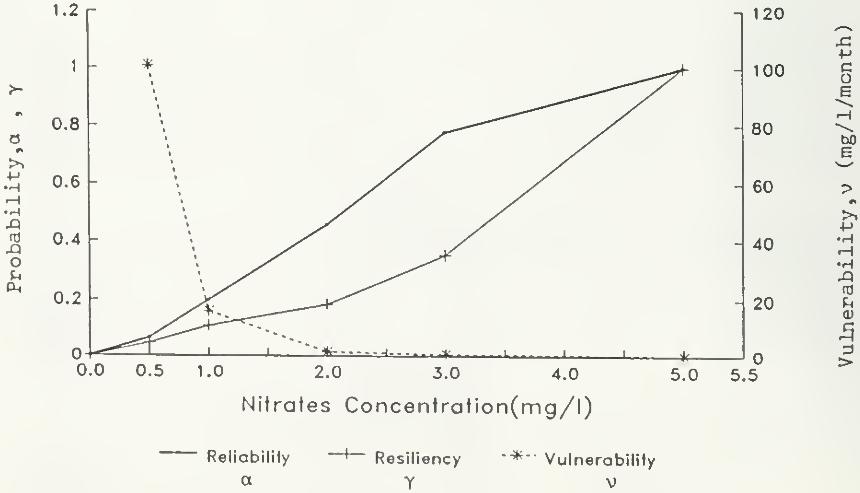

FIGURE 2(b)

Figure 2: Performance Evaluation Estimators for Total Phosphorus and Nitrates -- Grand River, Ontario

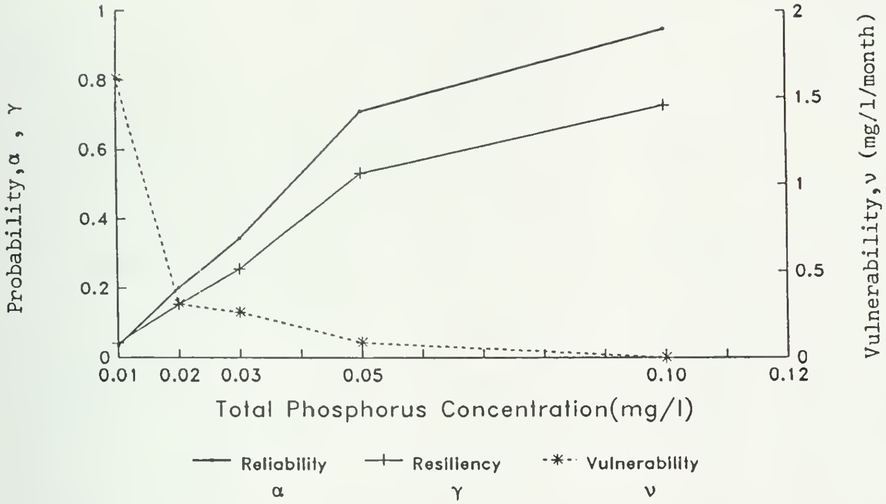

FIGURE 3(a)

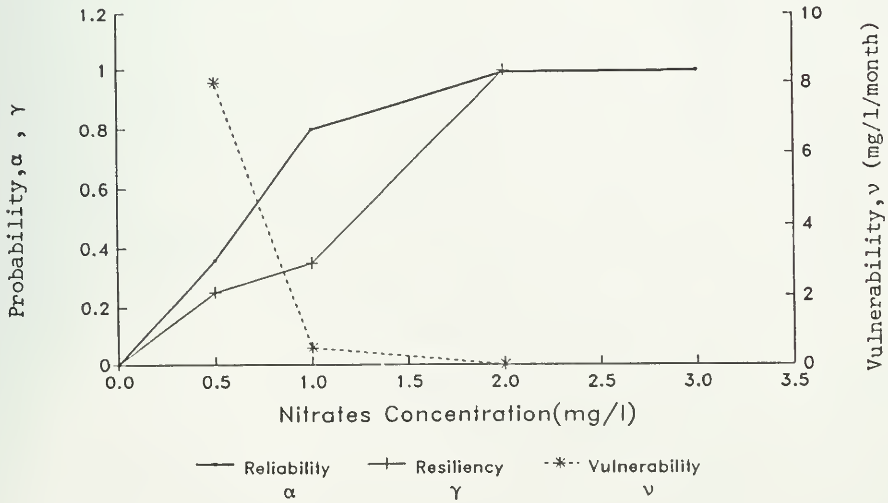

FIGURE 3(b)

Figure 3: Performance Evaluation Estimators for Total Phosphorus and Nitrates -- Saugeen River, Ontario

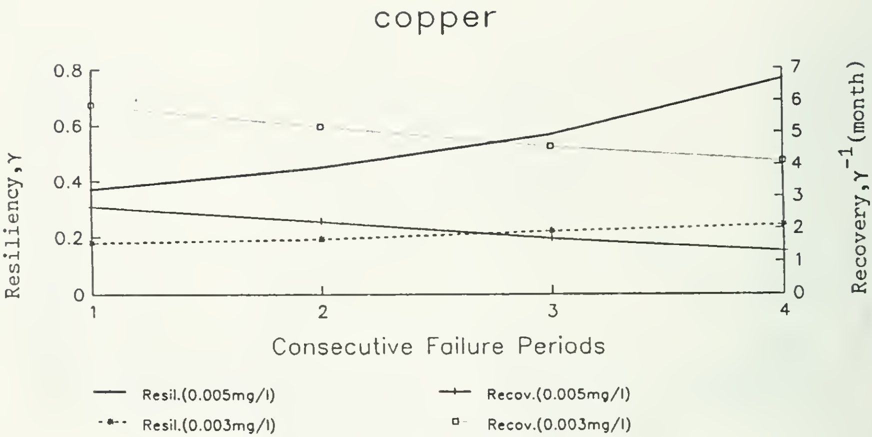

Figure 4: Effects of Change in Policy Objectives on Resiliency for Copper Concentration -- Saugeen River, Ontario